Evaluation of Ultrafiltration for Spacecraft Water Reuse

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Abstract

Ultrafiltration is examined for use as the first stage of a primary treatment process for spacecraft wastewater. It is hypothesized that ultrafiltration can effectively serve as pretreatment for a reverse osmosis system, removing the majority of organic material in a spacecraft wastewater. However, it is believed that the interaction between the membrane material and the surfactant found in the wastewater will have a significant impact on the fouling of the ultrafiltration membrane. In this study, five different ultrafiltration membrane materials are examined for the filtration of wastewater typical of that expected to be produced onboard the International Space Station. Membranes are used in an unstirred batch cell. Flux, organic carbon rejection, and recovery from fouling are measured. The results of this evaluation will be used to select the most promising membranes for further study.

Introduction

Worldwide, many communities have begun to consider water reuse the most economically feasible method for providing water to meet the needs of their populations. Industrial processes and landscape irrigation are common applications for recovered water. Some communities have begun to implement indirect potable reuse, in which treated wastewater effluent is discharged to a receiving water body that is the source of potable water for a community. The effluent receives some additional treatment due to the residence time of the water in the natural environment.

The National Aeronautics and Space Administration (NASA) has a unique requirement for water reuse. Of the various consumables required to sustain human life in space, water accounts for the greatest percentage of material by mass. It is estimated by Skoog, et al (1989) that between 3.63 and 12.63 kg of water / person are required for each mission day. Both the available spacecraft volume and the cost of launching the required mass into orbit limit the amount of water that can be carried onboard spacecraft for extended duration missions. Clearly, water must be recycled in order to make long duration missions feasible.

NASA requires a direct potable reuse system that will reliably produce potable water for consumption by a spacecraft crew for extended durations. As plans for extended duration missions are developed, new technologies for the reuse of water onboard spacecraft must be considered. In many water reuse projects, a large volume of fairly dilute effluent from a wastewater plant undergoes advanced water treatment processes to meet reclaimed water guidelines. In space applications, water recovery systems process a small volume of highly concentrated wastewater. In addition, power, volume, weight and chemical additions must be limited in order to meet the constraints of spaceflight. Finally, technologies used onboard space vehicles that transfer a crew between Earth and a planetary outpost must be capable of operating independent of gravity.

Materials and Methods

Membrane materials frequently used in the manufacture of ultrafiltration membranes include polysulfone (PS), polyethersulfone (PES), polyacrylonitrile (PAN), cellulose esters, polyimide (PI), polyetherimide (PEI), polyamide, and polyvinylidene fluoride (PVDF) (Anselme and Jacobs, 1996). Five ultrafiltration membrane materials were evaluated in this study. All membranes were manufactured by Osmonics, Inc. (Minnetonka, MN). The ultrafiltration membranes vary somewhat in their pore size ratings. Membranes were selected as close to a molecular weight cut-off (MWCO) of 100 kiloDaltons (kDa) as commercial availability allowed. Literature (Fane *et al*, 1985; Jönsson and Jönsson, 1991) and previous NASA testing (Bagdigian *et al*, 1992) indicated that polysulfone and polyethersulfone membranes experience significant fouling when exposed to ionic surfactants. Therefore, these membranes were not evaluated.

Table 1. Membrane materials.

Membrane material	Part number	Molecular Weight Cut-off (MWCO)
Polyvinylidenefluoride (PVDF)	Sepa AN09	30K
Polyacrylonitrile (PAN)	Sepa RM05	100K
Ultrafillic (proprietary)	Sepa MX50	100K
Thin-film composite (TFC)	Sepa G-80	10K
Cellulose acetate (CA)	Sepa SZ05	80K

Wastewater used in this study was collected from the main wastewater feed tank that is part of the Water Research Facility (WRF) located in Building 7B at Johnson Space Center. This wastewater was collected from volunteer donors. The wastewater is representative of wastewater that will be produced by a crew aboard the International Space Station and consists of shower waste, lavatory waste, oral hygiene waste, urine, urine flush water, and a humidity condensate analog.

There is substantial day-to-day variation in the concentration of both total organic carbon and dissolved solids in actual wastewater. The range of concentration and components of human urine produces in the most significant variability in the wastewater. In order to

minimize the effect of this variability, sufficient wastewater was collected at the start of the study for the entire set of membrane experiments. Wastewater was stored at 2 - 4°C (35.6 - 39.2°F) in a closed container when not in use to minimize biodegradation and volatilization of constituents. Composition of the wastewater is shown in Table 2.

Table 2. Wastewater composition. Composition represents wastewater produced by 4 crewmembers / day. (MSFC Specification 2841C, Table I)

Component	Quantity (liters)
Shower waste	10.9
Lavatory waste	16.4
Oral hygiene waste	1.5
Urine	6.0
Urine flush	2.0
Humidity condensate	9.1
Total volume	**45.9**

NASA Whole Body Shower Soap (NWBSS) was used as the personal care product for both the shower and lavatory users. The composition of NWBSS is shown in Table 3. The primary ingredient of NWBSS is Geropon TC-42 (BASF), which is an anionic surfactant.

Table 3. NASA Whole Body Shower Soap composition. (Ecolab, Inc. production specification, 1988)

Component		% composition (w/w)
Trade name (Manufacturer)	**Generic name**	
Geropon TC-42 (Rhodia)	Sodium cocoyl-n-methyl taurate	98.65
Emulmetik 300 (Lucas Meyer)	Lecithin	0.5
Luviquat FC 550 (BASF)	Polyquaternium-16	0.75
----	Formalin	0.1

Since a true humidity condensate can only be obtained through closed environment testing, an analog for humidity condensate is used. This analog includes major compounds found in actual humidity condensate collected from Space Shuttle missions, closed environmental chamber tests at Johnson Space Center, and the End-use Equipment Facility (EEF) at Marshall Space Flight Center. (Carter *et al*, 1992, Muckle *et al*, 1993; Straub *et al*, 1995; Pierre *et al*, 1996; Homan *et al*, 1997) The composition of the simulated humidity condensate is presented in Table 4.

Table 4. Composition of humidity condensate analog.

Compound	Concentration (mg/l)
Ethanol	129.7
2-Propanol	35.0
1-2, Propanediol	71.5
Caprolactam	26.1
2-(2-butoxyethoxy) ethanol	3.8
4-ethylmorpholine	4.2
Methanol	7.5
Formaldehyde	15.4
Formic Acid	21.9
Propionic acid	7.2
Zinc Acetate Dihydrate	43.9
Ammonium Bicarbonate	32.8
Ammonium Carbonate	32.3

The quality of the wastewater used in the filtration experiments is summarized in Table 5.

Table 5. Average wastewater composition.

Parameter	
pH	8.8
Total organic carbon	353 mg/l
Total suspended solids	
Total dissolved solids	

An unstirred batch filtration cell (Spectrum, model S-76-400, P/N 501819) was used for the experiments. This batch filtration cell employed dead-end filtration to produce permeate. By operating the system without stirring, the maximum adsorptive fouling of the membrane should be observed. Solute transport from the membrane into the bulk feed solution is due only to diffusive back transport. The conditions within the batch filtration cell at a given time are depicted in Figure 1. In this figure, C_{bulk} represents the solute concentration in the bulk liquid, C(x) is the solute concentration at distance X in concentration polarization layer; C_{mem} indicates the solute concentration at the membrane surface; and C_p represents the solute concentration in permeate. In addition, J_p in the flux of solvent through the membrane and P is the driving pressure.

The cell used a 76 mm diameter flat sheet membrane. The maximum allowable working pressure (MAWP) of the cell is 5.8 bar (70 psig). The working pressure is provided by pressurized facility breathing air and was controlled by a regulator (Porter, P/N 8286). The experiments were conducted at 2 bar (15 psig).

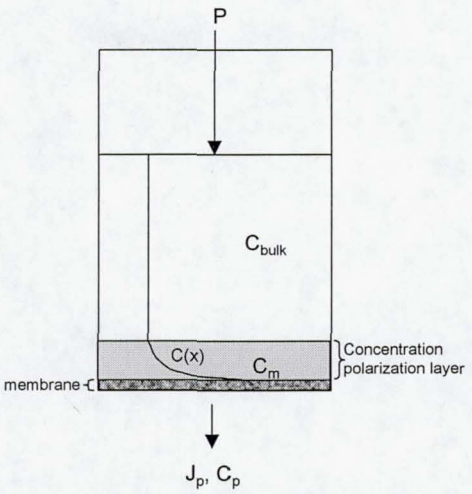

Figure 1. Concentration polarization in a batch filtration cell.

Each membrane was evaluated three times. A new membrane was used for each experiment. New membranes were rinsed with deionized water (DI), then soaked membrane-skin-down in DI water overnight (Cho *et al*, 1998; Jones and O'Melia, 2000; Childress and Elimelech, 1998). The membrane was removed from the DI water and rinsed again immediately before installation into the filtration cell.

The clean water flux of the membrane was measured prior to each dead-end filtration experiment. Two hundred and fifty milliliters of wastewater was then added to the filtration cell and filtered under constant pressure to at least 80% recovery. No makeup wastewater was added to the cell during the experiment. The mass of permeate collected over time was recorded with an electronic balance (Mettler-Toledo, PG-5002S) connected to a data acquisition system. At the completion of filtration, the concentrate was poured out of the cell and the membrane was rinsed with at least 250 ml of DI water. The clean water flux of the fouled membrane was then measured.

Results and Discussion

Membrane Performance

The steady-state flux through the membranes is illustrated in Figure 2. The thin-film composite membrane, although marketed as an ultrafiltration membrane, performed more like a nanofiltration membrane. The clean water flux of the membrane at an operating pressure of 2 bar was considerably lower than that of the other membranes; therefore, the membrane was not evaluated with wastewater.

The PVDF membrane exhibited the greatest steady-state flux of the membranes tested; however, the ultrafillic membrane's average steady-state flux was within the statistical error of the average flux of the PVDF membrane. Interestingly, the PVDF membrane

had the lowest MWCO rating, at 30 kDa, of the membranes evaluated. This is contrary to the expected results, in which the higher MWCO membranes would yield the greatest steady-state flux. Similar results were report by Archer (1999), who observed that permeate flux is not related to MWCO in the filtration of surfactant solutions.

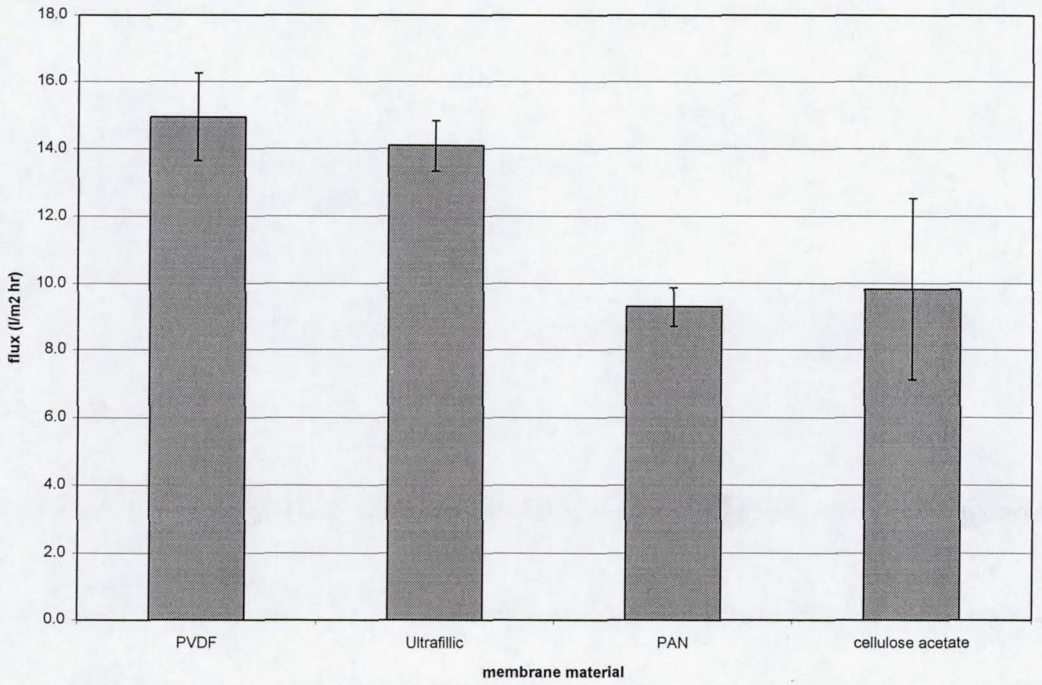

Figure 2. Steady-state flux of ultrafiltration membranes in dead-end filtration experiments.

The clean water flux of each membrane, both before and after fouling, is presented in Figure 3. Of the evaluated membranes, the PVDF membrane and the cellulose acetate membrane had the greatest clean water flux, while the ultrafillic and cellulose acetate membranes had the highest clean water flux after fouling. The PVDF membrane showed substantial irreversible fouling, based upon the clean water flux measured after filtration of the wastewater. The percent flux reduction of each membrane is summarized in Table 6. Very little correlation is observed between clean water flux reduction of a fouled membrane and the molecular weight cutoff as supplied by the manufacturer. The membranes that showed the greatest loss of flux after fouling were the two hydrophobic membranes, PVDF and PAN. This is likely due to the adsorption of surfactant to the hydrophobic surface of the membrane. Similar results have been reported in the literature (Laîné *et al*, 1989, Jönsson and Jönsson, 1991).

Table 6. Molecular weight cutoff and flux reduction

Membrane Material	MWCO (kDa)	surface	% clean water flux reduction
PVDF	30	hydrophobic	86.6
Cellulose acetate	80	hydrophillic	21.2
PAN	100	hydrophobic	71.7
"Ultrafillic"	100	hydrophillic	58.8

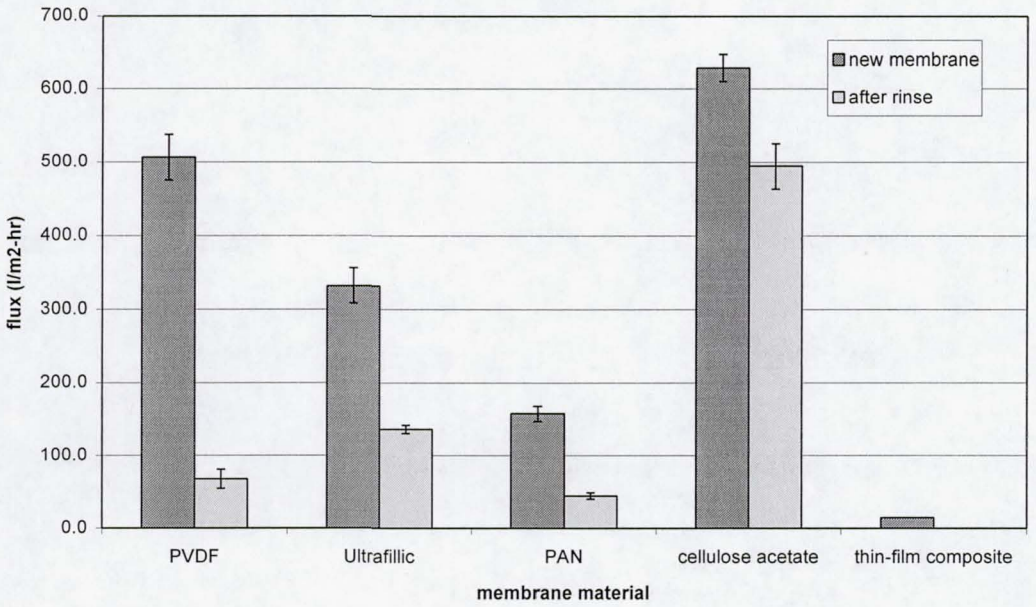

Figure 3. Clean water flux of membranes, before and after fouling.

Water Quality

Very little difference was observed in the permeate water quality between each membrane. In all cases, the permeate total suspended solids was below detection limits. The permeate turbidity was reduced to less than 1 NTU. The average permeate turbidity produced by each membrane is shown is Table 7. The turbidity of the permeate from the PVDF membrane was not measured.

Total organic carbon was measured during each experiment; however, the results of these measurements are inconclusive.

Table 7. Average permeate turbidity.

Membrane Material	Turbidity
PVDF	--
Cellulose acetate	0.324
PAN	0.296
"Ultrafillic"	0.325

Conclusions and Upcoming Work

Based upon the data collected, the PVDF, ultrafillic, and cellulose acetate membranes will be the subjects of additional study. In general, the hydrophilic membranes were less susceptible to fouling than the hydrophobic membranes. Furthermore, molecular weight cut-off was not a useful indicator of either steady-state flux or susceptibility to fouling.

Of the membranes evaluated, the proprietary "ultrafillic" membrane appears to be the most promising. The steady-state flux of the membrane measured during dead-end filtration experiments exceeds 14 l/m^2-hr. In addition, it showed good recovery from fouling, based upon measurements of clean water flux. The cellulose acetate membrane demonstrated excellent recovery from fouling, although the steady-state flux was 30% less than the ultrafillic membrane. The PVDF membrane, despite significant irreversible fouling, had the greatest steady-state flux of the membranes evaluated.

In upcoming work, a variety of surfactants frequently used in personal care products will be evaluated with the selected membranes. It is believed that an optimum combination of surfactants and membrane can be determined. The selected membranes will also be further characterized to confirm molecular weight cutoff and surface characteristics.